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Research on Active Damper Siting Strategy Based on Resonance Modal Analysis

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Abstract

In multi-inverter parallel grid-connected systems, harmonic resonance can lead to performance degradation and even instability. Although installing active dampers (ADs) is considered an effective approach to suppress harmonic resonance, research on the optimal installation positions for ADs is still limited, and specific optimization methods require further exploration. This paper proposes an AD siting strategy based on resonance modal analysis (RMA) and node participation factor (PF) calculations. The method aims to select the installation positions for AD by identifying the nodes that significantly contribute to harmonic resonance, and the validity of this approach is confirmed through modal sensitivity analysis. To address the challenge of conducting RMA with inverter black-box models, impedance models of the inverters are obtained through frequency scanning, and the nodal admittance matrix of the system is established. Additionally, this method considers the impact of changes in grid impedance on AD siting results. Finally, both simulation and experimental results validate the effectiveness of the proposed strategy.

Keywords: active damper (AD); harmonic resonance; resonance modal analysis (RMA); frequency scanning

1. Introduction

Scale solar, energy storage, and other new energy power stations typically adopt a structure where multiple grid-connected inverters are connected in parallel to the point of common coupling (PCC) [1]. However, interactions among inverters and between inverters and the grid can easily lead to harmonic overvoltage or even resonance instability in parallel systems, posing significant threats to the safe and stable operation of the system [2]. Therefore, it is crucial to effectively suppress system resonance to ensure system stability and reliability.

Resonance suppression methods for inverters have been the subject of extensive study, with passive and active damping techniques being commonly employed. Passive damping, which involves adding resistors in series or parallel to the inverter output filter to increase damping [3], incurs additional power loss and exhibits poor adaptability under a weak grid. Active damping methods, by contrast, generally provide additional resonance damping to the system by introducing a control unit into the control loop [4,5] or

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adding additional control loops [6–8]. However, these methods usually necessitate modifications to the internal structure or parameters of the grid-connected inverters, rendering them unsuitable for new energy power plants with undisclosed internal structure and parameters. Previous studies have indicated that installing active dampers (ADs) effectively suppresses wideband oscillations [9–11]. ADs control the frequency of resonance to act as a virtual resistor, thereby enhancing system damping at resonance frequencies and improving the impedance stability of grid-connected inverter systems. This solution does not necessitate modifications to the inverters' control strategy or parameters, enhancing its applicability. Typically, the PCC is considered the optimal installation position for ADs, but there is a lack of effective theoretical proof. Current research on ADs typically analyzes single-inverter systems or idealizes the line impedance between each parallel-connected inverter node and the PCC. However, in large-scale new energy power plants, significant line impedances exist, along with differences among these line impedances. Thus, the grid-connected system's resonance problem is influenced not only by the output impedance of the inverter and the grid impedance but also by the line impedance. This variability introduces more options for AD installation positions, making the determination of the optimal installation location through system resonance analysis a worthwhile research topic.

Harmonic analysis of multi-inverter systems is commonly performed using methods based on system transfer functions. These methods involve constructing the transfer function of the inverter's impedance model and applying impedance analysis to assess system stability [12–14]. Research highlighted in [15] has detailed the system's closed-loop transfer function matrix, revealing the coupling relationships between each inverter's output currents and the reference currents of other inverters, and examining the impact of asynchronous digital control clocks on system resonance characteristics. Another study [16] introduced a closed-loop interconnected model for multi-inverter systems, evaluating the effect of inverter interactions on system stability by comparing the open-loop and corresponding closed-loop eigenvalues and considering the role of collecting line lengths in overall stability. However, these transfer function-based methods face difficulties in effectively determining the contribution of individual nodes to harmonic resonance, providing limited insights for optimal AD placement. Moreover, the complexity of the transfer function escalates with an increasing number of inverters, complicating the analysis.

In addition to methods based on system transfer functions, resonance modal analysis (RMA) has received increasing attention in recent years. Building on the establishment of the nodal admittance matrix for a multi-inverter grid-connected system, the application of RMA enables a detailed investigation of the system's resonance. This approach facilitates the extraction of resonance-related information, such as node participation factors (PFs) [17–21], which quantify the contribution of specific nodes to the system's resonance. The node with the highest PF is considered the focal point of harmonic resonance in the system. By adjusting the nodal impedance at nodes with high PFs using ADs, effective suppression of harmonic resonance can be achieved. However, constructing the nodal admittance matrix requires knowledge of the electrical parameters of the devices connected to each node. Inverter parameters are often confidential and inaccessible, resulting in black-box models that hinder the direct application of RMA to analyze system resonance.

This paper proposes an AD siting strategy based on RMA. The contributions of this paper are as follows:

- (1) RMA is utilized to determine the optimal installation location of the AD in multi-inverter parallel grid-connected systems. The node with the highest participation factor is selected as the optimal installation site for the AD, as it represents the critical focal point of harmonic resonance in the system. Compared with conventional non-

targeted approaches, this targeted placement significantly improves the efficiency of resonance suppression.

- (2) In response to the challenges posed by the application of RMA in systems with inverter black-box models, this study utilizes frequency scanning to obtain the external characteristic impedance model of inverters. This model is then employed to construct the system's nodal admittance matrix, thereby obviating the need to develop transfer function-based models for the inverters.
- (3) This study extends the analysis to investigate the impact of grid impedance variations on AD siting results. The impact is primarily generated by the grid reactance, with its increase leading to a decrease in resonance frequency. However, the relative ordering of PFs among the nodes remains stable, without abrupt changes, across a specific range of grid impedance variations. Consequently, within this delineated range of grid impedance fluctuations, AD siting results remain unchanged.

2. AD Siting Strategy

2.1. System Description

A multi-inverter grid-connected system is illustrated in Figure 1a. The system comprises n grid-connected inverters, with each inverter connected to the PCC through a line impedance. The grid is represented by a Thevenin equivalent circuit consisting of the equivalent grid impedance Z_g and a voltage source V_g . The line impedance of the i th inverter ($i = 1, 2, \dots, n$) is denoted as $Z_{l,i}$. Despite the stability of individual inverter control loops, interactions among the current control loops of the inverters can induce harmonic resonance within the system [8]. If the line impedance of each inverter varies, the contribution of inverters at different locations to harmonic resonance may differ. Therefore, traditional installation of ADs at the PCC may not achieve optimal resonance suppression effects. Hence, this paper introduces a siting strategy designed to pinpoint the inverter location contributing most significantly to harmonic resonance, recommending the installation of an AD at this critical position to mitigate harmonic resonance.

Figure 2 illustrates the Norton equivalent model of the multi-inverter grid-connected system shown in Figure 1a. In this depiction, Node 1 is exemplified as the installation position for the AD, and both the inverter and the AD are represented using Norton equivalent circuits. $I_{s,i}$ and Z_i represent the equivalent current source and output impedance of the i th inverter, respectively, while $I_{s,ad}$ and Z_{ad} denote the equivalent current source and output impedance of the AD. $I_{s,ad}$ is designed to follow the fundamental current reference, aiming to stabilize the DC-link capacitor voltage by controlling the fundamental current. In this paper, the control method for the AD is shown in Figure 1b [10]. The control principle of the AD is similar to that of the resistor active power filter (R-APF) [11], aiming to synthesize a virtual resistor R_v at harmonic frequencies by controlling the harmonic components of its output current in proportion to the voltage's harmonic components at the node where it is parallel-installed. If the current loop gain of the AD is sufficiently large or the virtual resistor control loop is adjusted, $Z_{ad} \approx R_v$ can be achieved [9]. Thus, the AD can provide active damping resistance at the harmonic frequency. The impedance model of the AD in this paper is equivalently represented as R_v for analytical convenience.

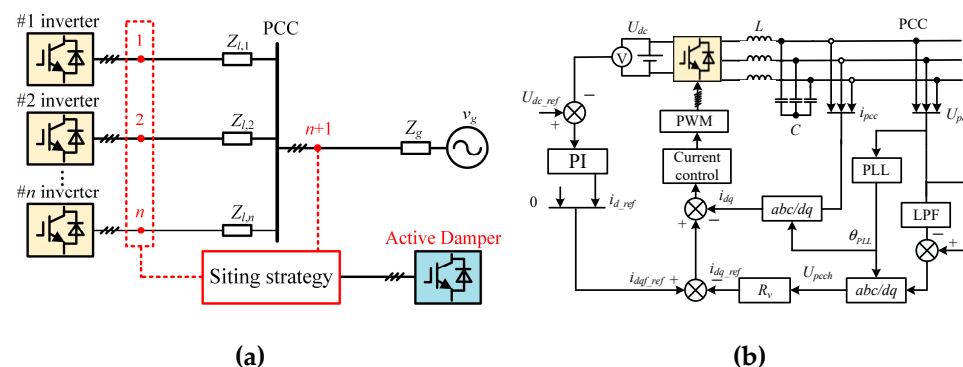


Figure 1. System topology and control diagram of the multi-inverter grid-connected system: (a) Topology of the multi-inverter parallel grid-connected system. (b) Control block diagram of the AD.

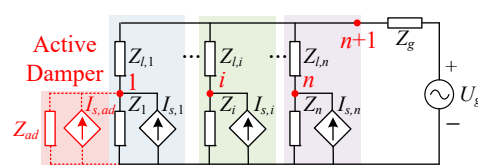


Figure 2. Norton equivalent model of a multi-inverter grid-connected system.

2.2. Siting Strategy Based on RMA

The RMA method analyzes system harmonic resonance based on the nodal admittance matrix. By calculating PFs for each node, the contribution of each node to the system's harmonic resonance can be assessed, and the node with the highest PF can be identified as the center of the system's harmonic resonance [19,20]. Accordingly, this paper employs RMA to analyze resonance in the system and to identify the optimal installation position for the AD. The fundamental analytical procedure of the RMA is described below.

The relationship between the voltage and current at each node can be described through the nodal admittance matrix Y at a specified frequency f , denoted as [18]

$$U = Y^{-1}I \quad (1)$$

where U and I represent the nodal voltage matrix and nodal current matrix, respectively. If the system experiences resonance at frequencies where Y approaches singularity, significant values will be present within Y^{-1} . This condition results in specific elements in U being relatively large, indicating overvoltage at corresponding nodes [19].

RMA essentially transforms (2) from its original physical coordinate system into the modal coordinate system. Firstly, to investigate the singularity of Y , perform eigenvalue decomposition, yielding

$$Y = LAT \quad (2)$$

where A is a diagonal matrix of eigenvalues; L and T represent the left and right eigenvector matrices, respectively, with $L = T^T$. For $n+1$ nodes, L is composed of column eigenvectors $l_1, \dots, l_{n+1}$, and T is composed of row eigenvectors $t_1, \dots, t_{n+1}$. Substituting (3) into (2) yields

$$V = A^{-1}J. \quad (3)$$

$V (=TU)$ and $J (=TI)$ represent the modal voltage and current vectors, respectively. Here, the elements V_k and J_k ($k = 1, 2, \dots, n+1$) represent the linear mappings of

nodal voltage and nodal current along the k th eigenvector direction. Therefore, for the system depicted in Figure 1a, (1) can be expressed in modal coordinates as (3), denoted as

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_{n+1} \end{bmatrix} = \begin{bmatrix} \lambda_1^{-1} & 0 & \cdots & 0 \\ 0 & \lambda_2^{-1} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_{n+1}^{-1} \end{bmatrix} \begin{bmatrix} J_1 \\ J_2 \\ \vdots \\ J_{n+1} \end{bmatrix}. \quad (4)$$

By transforming the system of equations from the original physical coordinate system to the modal coordinate system, decoupling them into a set of independent equations facilitates the identification of the frequency and amplitude of each resonance mode in the system. The inverse of the k th eigenvalue λ_k is defined as the modal impedance z_k . When z_k exhibits a resonance peak, even a small value of J_k may result in a significantly large modal voltage V_k . Notably, since A is a diagonal matrix, z_k only influences the corresponding modal voltage V_k , without affecting other modal voltages. Hence, by evaluating the magnitudes of modal impedances, the locations of system resonance can be identified.

At the point of system resonance, a critical mode c ($c \in (1, \dots, n+1)$) emerges, characterized by its modal impedance z_c reaching a maximum value at the resonance frequency, significantly surpassing the modal impedances of other modes. Consequently, according to (2) and the definition of modal impedance, (1) can be represented by the modal impedances and eigenvectors for each mode, with the resonance condition being simplified through the critical mode at the resonance frequency, as shown in (5).

$$U = \sum_{k=1}^{n+1} z_k l_k t_k I \approx z_c l_c t_c I = z_c S_c I. \quad (5)$$

where S_c represents the PF matrix corresponding to the critical mode c . From (5), it can be observed that the elements in S_c illustrate the varying degrees of influence that currents at different nodes exert on the voltage at a specific node. Additionally, the elements in S_c reflect the sensitivity of nodal admittance elements to the critical eigenvalue λ_c [22], with the corresponding relationship expressed as

$$S_c(i, j) = \frac{\partial \lambda_c}{\partial Y(j, i)} = l_{ic} t_{cj}. \quad (6)$$

For Node k , the PF of critical mode c is defined as $PF_{kc} = S_c(k, k)$. According to (3), it can be seen that the left and right eigenvectors represent, respectively, the excitability and observability of the critical mode c at each node [19]. Therefore, the PF combines excitability and observability into a unified index, representing the risk of resonance occurrence at the node. Assuming that the AD is paralleled at Node k , only the element $Y(k, k)$ in Y is modified, expressed as

$$Y(k, k) = \left(G_{kk} + \frac{1}{R_v} \right) + jB_{kk}. \quad (7)$$

G_{kk} and B_{kk} represent, respectively, the real and imaginary components of $Y(k, k)$ before adding the AD, representing nodal conductance and susceptance, respectively. Equation (7) illustrates that the AD contributes to damping by increasing G_{kk} . However, the effect of different installation nodes on the peak impedance of the critical mode varies. To quantitatively analyze these differences, this paper utilizes the modal sensitivity of

nodal conductance to reflect the relationship between nodal conductance and the magnitude of critical eigenvalues. The modal sensitivity of the nodal conductance for the critical mode is calculated as

$$\frac{\partial |\lambda_c|}{\partial G_{kk}} = \frac{\partial |\lambda_c|}{\partial |\lambda_c|^2} \frac{\partial |\lambda_c|^2}{\partial G_{kk}} = \frac{PF_{kc,R} \lambda_{c,R} + PF_{kc,I} \lambda_{c,I}}{|\lambda_c|} \quad (8)$$

where the subscripts R and I represent the real and imaginary parts of the complex variables, respectively. Due to the fact that the imaginary part of the PF and the resonance modal impedance can be considered close to zero [23], the modal sensitivity of nodal conductance can be expressed by the PF, specifically, $\partial |\lambda_c| / \partial G_{kk} \approx PF_{kc}$. Therefore, installing the AD at the node with higher PF results in better suppression of modal impedance. Hence, this paper employs PFs for each node as the basis for AD siting, selecting the node with the highest PF as the installation location for the AD.

However, for new energy power stations with modularly designed internal structures and undisclosed parameters, inverters constitute black-box models, meaning the output impedance Z_i of the inverters cannot be obtained through conventional theoretical modeling. This limitation precludes the direct application of modal analysis methods for resonance analysis of the system.

To address this challenge, this paper introduces a method for constructing the nodal admittance matrix based on the frequency scanning data of the inverter impedance, facilitating RMA of the system and aiding in the siting of AD. This approach enables RMA without the need for transfer function-based models of the inverters. The fundamental process of the AD siting strategy is illustrated in Figure 3. Initially, voltage or current perturbations within a specific frequency range are injected into the output ports of the grid-connected inverter while it is offline. The external characteristic impedance of the inverter is then calculated using Fourier analysis based on the harmonic frequency response [24]. Subsequently, the system's nodal admittance matrix is established, followed by RMA. Based on the outcomes of the RMA, the node with the highest PF is selected as the installation position for the AD.

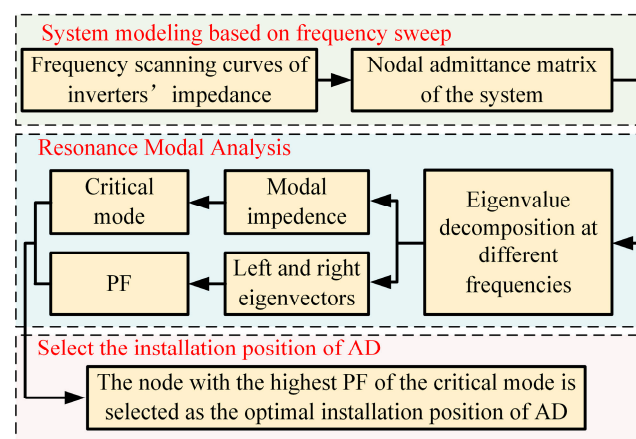


Figure 3. Flow diagram of the AD siting strategy.

3. Case Study

It is known that multi-inverter parallel systems and dual-inverter parallel systems exhibit similar resonance characteristics [19,20]. Consequently, for the sake of analysis, a dual-inverter setup is adopted as a representative model to explore the system's resonance characteristics, rather than employing a more complex multi-inverter configuration. Generally, the circuit parameters and control settings of inverters in a power station remain

largely consistent, but the length of the collecting line may vary. Table 1 presents the inverter parameters, grid impedance, and two variants of line impedance parameters within a dual-inverter system.

Table 1. System parameters.

Parameter	Symbol	Value
Grid voltage	V_g	220 V
Inverter dc voltage	V_{dc}	1080 V
Filter inductance	L	3 mH
Filter capacitor	C	274 μ F
Line impedance 1	$Z_{l,1} (R_{l,1}, L_{l,1})$	0.8 m Ω , 0.174 mH
Line impedance 2	$Z_{l,2} (R_{l,2}, L_{l,2})$	17 m Ω , 0.348 mH
Grid impedance	$Z_g (R_g, L_g)$	5 m Ω , 0.02 mH

3.1. AD Siting for Case Study

In alignment with the AD siting procedure outlined in Figure 3, the initial phase entails conducting offline frequency scanning to assess the inverter's impedance. Figure 4 presents the outcomes of frequency scanning conducted on the output impedance of a single inverter.

For the dual-inverter configuration model, based on the frequency scanning data obtained for the inverter output impedance and the node numbering set in Figure 1, the system admittance matrix is derived according to (1) and shown in (9). RMA is then performed, and the results are illustrated in Figure 5. As seen in Figure 5, both Mode 2 and Mode 3 exhibit resonance, with resonance frequencies identified at approximately 700 Hz and 500 Hz, respectively.

$$Y = \begin{bmatrix} \frac{1}{Z_1} + \frac{1}{Z_{l,1}} & \cdots & 0 & 0 & -\frac{1}{Z_{l,1}} \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \cdots & \frac{1}{Z_{n-1}} + \frac{1}{Z_{l,n-1}} & 0 & -\frac{1}{Z_{l,n-1}} \\ 0 & \cdots & 0 & \frac{1}{Z_n} + \frac{1}{Z_{l,n}} & -\frac{1}{Z_{l,n}} \\ -\frac{1}{Z_{l,1}} & \cdots & -\frac{1}{Z_{l,n-1}} & -\frac{1}{Z_{l,n}} & \sum_{i=1}^n \frac{1}{Z_{l,i}} + \frac{1}{Z_g} \end{bmatrix} \quad (9)$$

Subsequent calculations of the PFs for each node in relation to the critical mode, as specified in (6), are displayed in Table 2. From Table 2, it is evident that the critical nodes for the resonance frequencies of 700 Hz and 500 Hz are Node 1 and Node 2, respectively. Consequently, following the AD siting strategy illustrated in Figure 3, an AD is recommended to be installed at Node 1 to mitigate the resonance at 700 Hz and at Node 2 to suppress the resonance at 500 Hz. Additionally, the modal sensitivity of the nodal conductance for the critical mode was calculated according to (8), and the results are shown in Table 3. The conductance sensitivities in Table 3 are approximately equal to the PFs in Table 2, validating the reasonableness of AD siting based on the PFs.

Table 2. Nodal PFs under critical modes.

Frequency/Hz	Node 1	Node 2	Node 3
700 (Mode 2)	0.979	0.013	0.008
500 (Mode 3)	0.012	0.984	0.004

Table 3. Sensitivity of node conductance.

Frequency/Hz	Node 1	Node 2	Node 3
700 (Mode 2)	0.969	0.013	0.008
500 (Mode 3)	0.013	0.980	0.004

Figure 6a,b present the RMA results when an AD is installed at Node 1 and Node 2, respectively. Three typical values of R_v , i.e., 50 Ω , 30 Ω , and 10 Ω , are adopted for parametric analysis. Comparison with the results from Figure 5 reveals that, with $R_v = 50 \Omega$, the amplitude of the modal impedance for Mode 2 in Figure 6a decreases from 127.7 Ω to 36.5 Ω . Moreover, as the setting of R_v decreases, the attenuation of the modal impedance amplitude for Mode 2 increases. Figure 6 only reflects this tendency that smaller R_v yields a better damping effect, which demonstrates that the damping performance is sensitive to the variation in R_v . However, the reduction in the modal impedance amplitude for Mode 3 is not as pronounced. As shown in Figure 6b, the modal impedance amplitude for Mode 3 decreases from 55.7 W to 26.6 Ω , and as the setting of R_v decreases, the attenuation in the modal impedance amplitude for Mode 3 increases, whereas the reduction in the modal impedance amplitude for Mode 2 is less noticeable. These observations in Figure 6 indicate that the capability of the AD to suppress the amplitude of the critical modal impedance aligns with the PF and modal sensitivity distribution across the nodes, validating the effectiveness of AD siting based on the PFs.

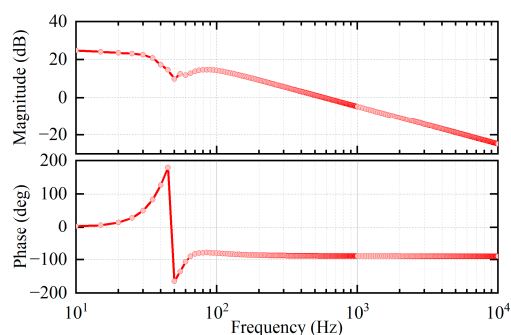
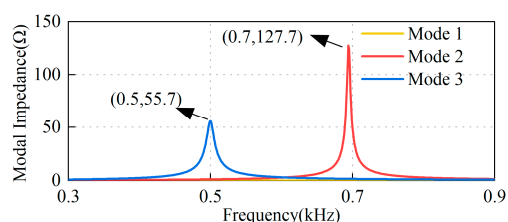
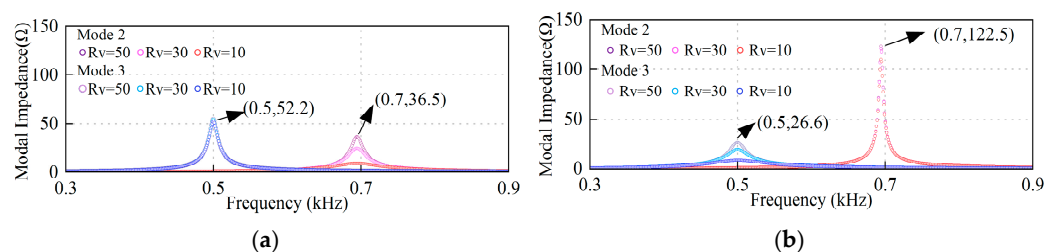
**Figure 4.** Impedance measurement results of a single inverter.**Figure 5.** Modal impedance of the dual-inverter system.

Figure 6. Modal impedance variations upon AD installation at various nodes: (a) at Node 1 and (b) at Node 2.

3.2. Impact of Grid Impedance Variations

The paper further explores the influence of grid impedance variations on the siting results. Utilizing the data from Table 1, the values of L_g and R_g are sequentially varied within a certain range. Given the typically static layout of power station systems, it is assumed that the inverter line impedances remain constant. Under these conditions, PFs of nodes at the resonance frequency are calculated by RMA, as shown in Figure 7.

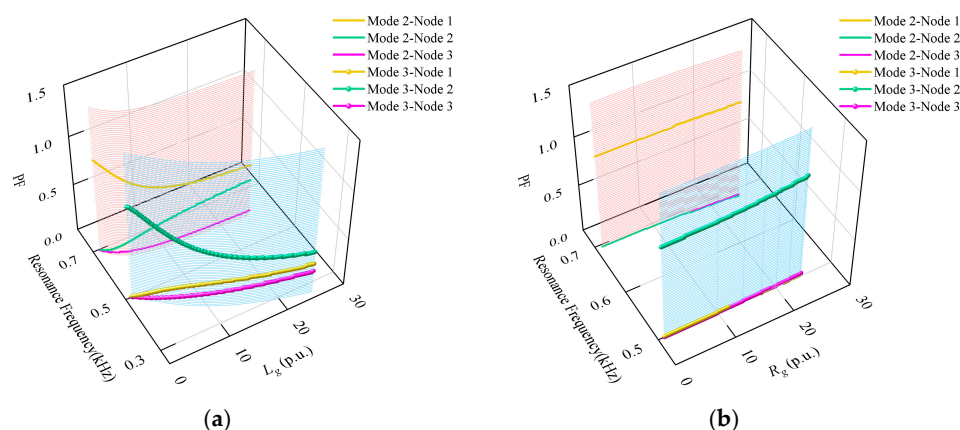


Figure 7. Results of RMA with varying grid impedance. (a) L_g . (b) R_g .

Figure 7a shows that as L_g increases, both Mode 2 and Mode 3 shift towards lower frequencies, with the resonance frequency of Mode 3 experiencing a notably larger change than that of Mode 2. The PFs of the two modes change smoothly without abrupt variations. Additionally, the order of magnitudes for Nodes 1 and 2 in both modes remains unchanged, indicating that the siting results remain unchanged. Figure 7b demonstrates that with an increase in R_g , there are no significant changes in either the resonance frequency or the PFs of nodes.

These observations show that the impact of grid impedance variations on the resonance frequency and PFs is mainly caused by grid reactance. Specifically, grid reactance has a more pronounced effect on critical modes with lower resonance frequencies than on those with higher frequencies. Moreover, for power station systems with a stable line layout, the siting results remain relatively stable within a specific range of grid impedance variations, with no abrupt changes observed.

4. Hardware-in-the-Loop Simulation Verification

As shown in Figure 8, a hardware-in-the-loop (HIL) simulation platform based on RT-LAB was established to evaluate the positions of AD as determined in Section 3. The multi-inverter grid-connected system is composed of an AD control box and a dual-inverter control box based on the 28377DSP. The simulation parameters for this system are presented in Table 1.

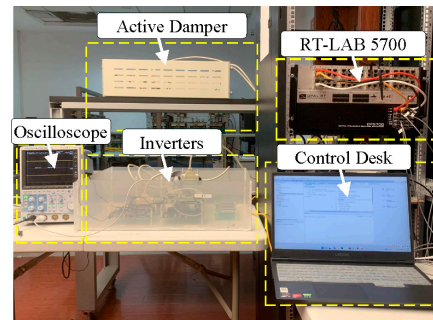


Figure 8. HIL simulation platform.

4.1. RMA Verification

To validate the accuracy of the resonance frequency identification results and the correctness of the nodal PF calculations using the RMA, harmonic currents were injected into the three nodes. The injected harmonic currents contained frequencies of 500 Hz and 700 Hz. Figure 9 presents the FFT analysis results of the voltage at each node under these two scenarios.

As shown in Figure 9a, after injecting harmonic current into Node 1, a significant harmonic voltage around 700 Hz is observed at Node 1, while no significant harmonics are present in the voltages of other nodes. This result indicates that the 700 Hz harmonic current injected into Node 1 uniquely excites the corresponding resonance peak in U_1 , identifying Node 1 as the critical node for the 700 Hz resonance frequency. As shown in Figure 9b, after injecting harmonic current into Node 2, a significant harmonic voltage around 500 Hz is observed at Node 2, while no significant harmonics are present in the voltages of other nodes. This result indicates that the 500 Hz harmonic current injected into Node 2 uniquely excites the corresponding resonance peak in U_2 , identifying Node 2 as the critical node for the 500 Hz resonance frequency. In Figure 9c, none of the three nodes show significant harmonic voltages, indicating that Node 3 has a low PF for both the 500 Hz and 700 Hz harmonic resonances. These simulation results corroborate the PF calculations in Table 2, thereby verifying the effectiveness and accuracy of the RMA.

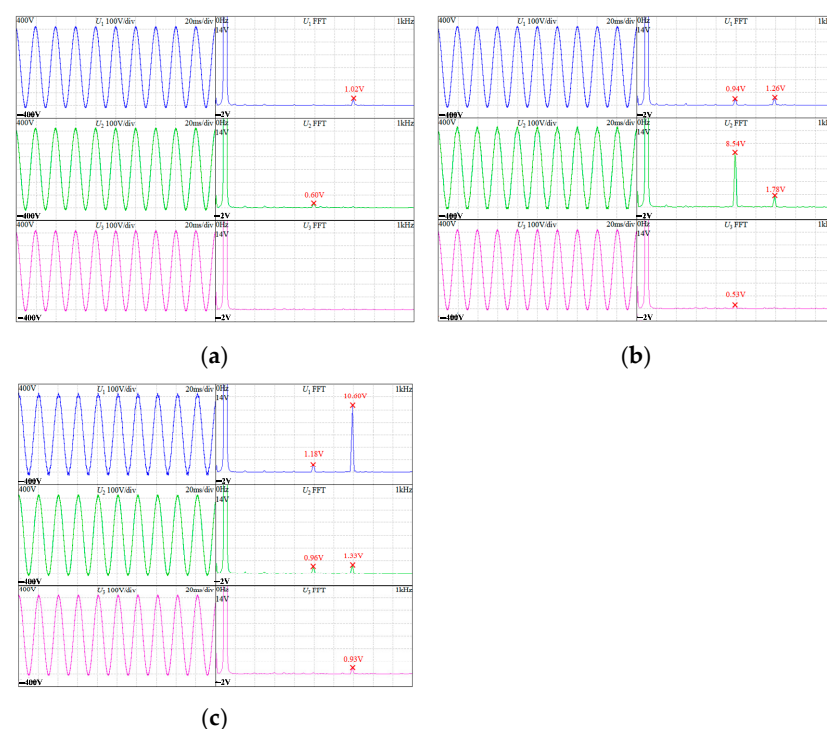


Figure 9. Harmonic spectra of nodal voltages after injecting harmonic currents at different nodes: (a) Injected at Node 1. (b) Injected at Node 2. (c) Injected at Node 3.

4.2. Verification of Siting Strategy Effectiveness

To illustrate the impact of the installation position of the AD on the suppression of critical modes, the simulation scenario corresponding to Figure 9a is used as an example. ADs were installed at the three nodes, and the simulation results are shown in Figure 10, with R_v set to $2\ \Omega$. As shown in Figure 10a, the harmonic voltage amplitude around 700 Hz at Node 1 significantly decreases from 10.60 V in Figure 9a to 1.68 V. However, in Figure 10b,c, there are no significant changes in the harmonic voltage spectra compared to Figure 9a. These results indicate that Node 1, identified as the critical node for the 700 Hz mode, effectively suppresses the 700 Hz harmonic voltage when an AD is installed at this node. This demonstrates that, compared to the traditional method of installing ADs at Node 3, the AD siting strategy based on resonance mode analysis can accurately identify critical nodes for harmonic resonance and achieve better suppression of harmonic resonance.

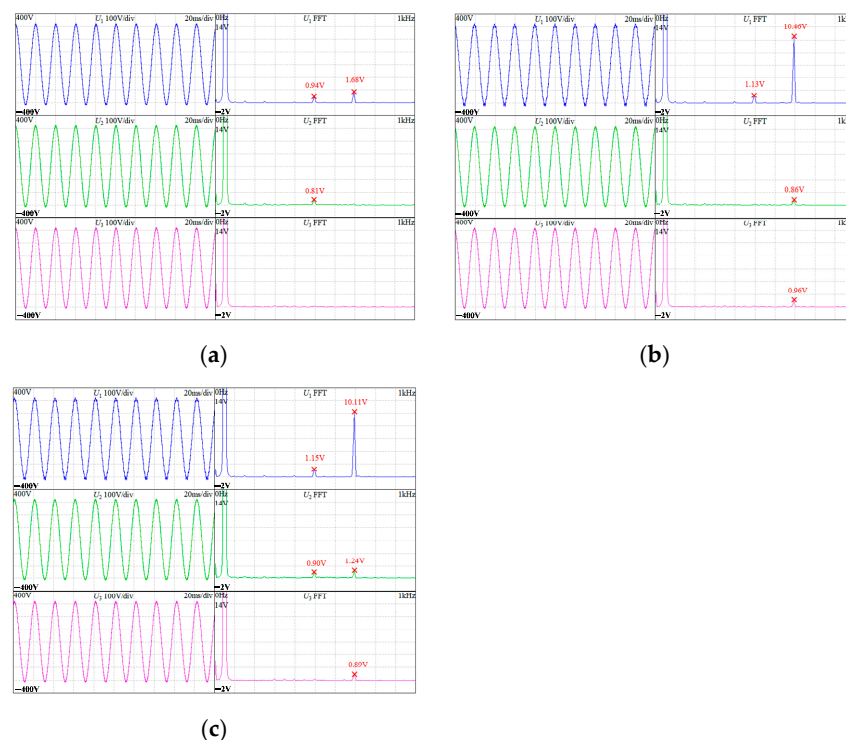


Figure 10. Harmonic spectra of nodal voltages with AD installation: (a) Installed at Node 1. (b) Installed at Node 2. (c) Installed at Node 3.

4.3. Impact Verification of Changes in Grid Impedance

Due to the significant impact of grid impedance on Mode 3, as shown in Figure 7, and with Node 2 identified as the critical node for Mode 3, additional simulations were designed based on the scenario in Figure 9b to verify the impact of grid impedance on the siting results.

On one hand, L_g was increased to 20 p.u., and harmonic current was injected into Node 2. Considering that the resonance frequencies of Mode 3 and Mode 2 are 300 Hz and 600 Hz, respectively, as shown in Figure 7, the injected harmonic current contained harmonics at 300 Hz and 600 Hz. The simulation results, including cases without AD installation and with ADs installed at each of the three nodes, are shown in Figure 11. As shown

in Figure 11a, U_1 and U_2 exhibit significant harmonic voltages around the 300 Hz and 600 Hz frequencies, with the amplitude relationships consistent with the PFs in Figure 7a. Due to the increased PF of Node 3 in Mode 3, U_3 also shows harmonic voltage around 300 Hz with an amplitude close to U_1 . Unlike Figure 10, where different installation positions show significantly different resonance suppression effects, the results in Figure 11b–d indicate that installing ADs at any of the three nodes can effectively suppress resonances, with Node 2 showing the best suppression effect for harmonic voltage around 300 Hz. The reason for this is that the difference in PFs among nodes decreases when L_g is 20 p.u., and Node 2 remains the critical node for Mode 3.

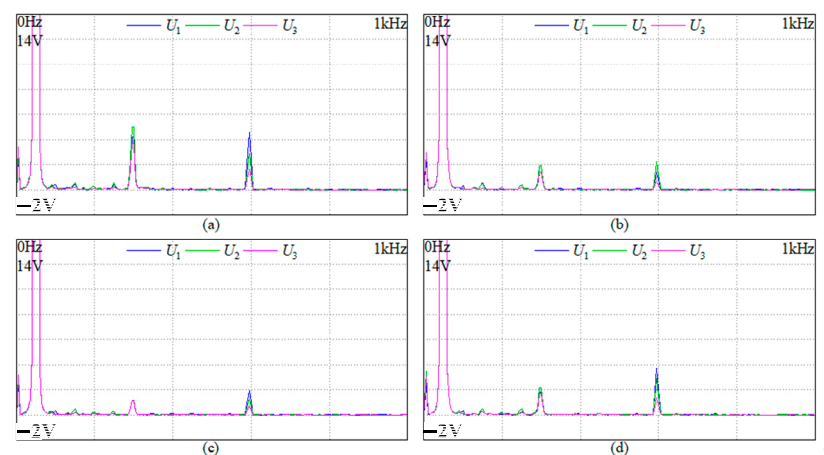


Figure 11. Harmonic spectra of nodal voltages with changes in L_g : (a) Without AD. (b) AD installed at Node 1. (c) AD installed at Node 2. (d) AD installed at Node 3.

On the other hand, R_g was increased to 20 p.u., and harmonic current was injected into Node 2. Considering that changes in R_g have little effect on modal resonance frequencies, as shown in Figure 7, the injected harmonic current contained harmonics at 500 Hz and 700 Hz. The simulation results, including cases without AD installation and with ADs installed at each of the three nodes, are shown in Figure 12. Similar to Figure 9b, Figure 12a shows that only Node 2 exhibits significant harmonic voltages around 500 Hz, demonstrating that the distribution of PFs at R_g of 20 p.u. is basically the same as that at R_g of 1 p.u. Additionally, the results in Figure 12b–d indicate that only Node 2 effectively suppresses harmonic voltages around 500 Hz, further confirming that Node 2 is the critical node for the 500 Hz resonance frequency. These simulation results are consistent with the analysis results in Figure 7.

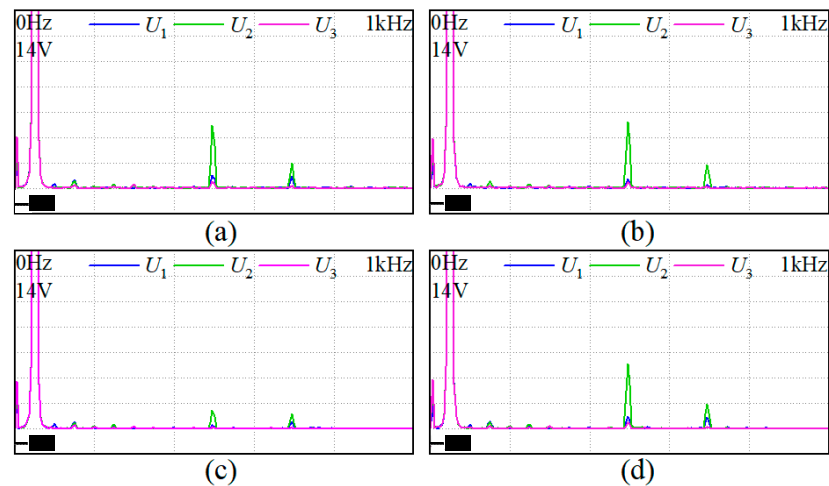


Figure 12. Harmonic spectra of nodal voltages with changes in R_g : (a) Without AD. (b) AD installed at Node 1. (c) AD installed at Node 2. (d) AD installed at Node 3.

5. Experimental Validation

5.1. Construction of Experimental Platform

Experimental verification is implemented based on the topology structure shown in Figure 1. To further verify the engineering practicability of this configuration and validate the theoretical analysis and control strategy proposed in this paper, a physical experimental platform for a multi-inverter grid-connected system is constructed. The hardware composition and parameter settings of the experimental topology are illustrated in Figure 13.

The platform consists of two inverters and one active damper, as well as the corresponding control system and electrical wiring. Parameters are different from the above HIL simulation setup, and detailed values are provided in Table 4. Identical controller parameters are configured for the two inverters. The power supply system of the experimental platform comprises a DC power source and an AC power supply (PRE2009S). The control system of the active damper is realized based on the RTU-BOX206 real-time digital controller.

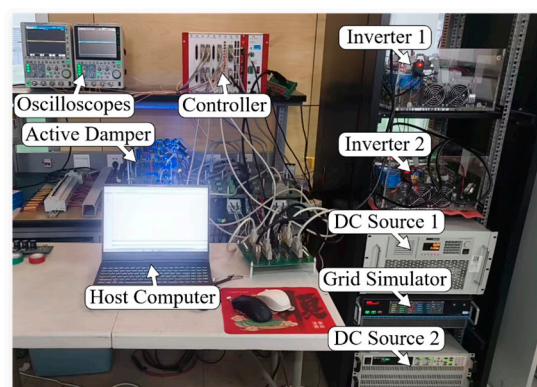


Figure 13. Overall photo of the experimental platform.

Table 4. Experimental parameter settings.

Parameter	Value	Parameter	Value
Inverter dc voltage V_{dc}	300 V	PCC voltage V_{pcc}	147 V
Rated active power P_n	1.2 kW	Switching frequency f_s	10 kHz

Fundamental frequency f_1	50 Hz	Filter capacitor C	20 μF
Filter inductance L	10 mH	Grid inductance L_g	5 mH
Line inductance 1 $L_{l,1}$	2 mH	Line inductance 2 $L_{l,2}$	3 mH

5.2. RMA Analysis

Based on the proposed siting strategy and the node numbering defined in Figure 1, the system modal impedances are calculated, and the results are illustrated in Figure 14. It can be seen that resonant peaks appear in both Mode 2 and Mode 3, with corresponding resonant frequencies of approximately 750 Hz and 300 Hz, respectively. Accordingly, the 750 Hz and 300 Hz resonant frequencies are selected for analysis in this experimental case.

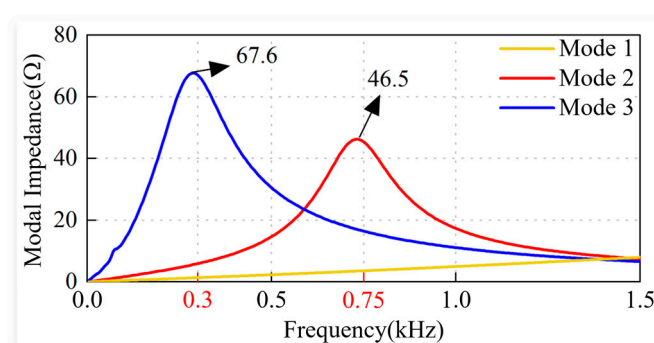


Figure 14. Experimental system modal analysis results.

The node participation factor corresponding to each node is further calculated, and the results are summarized in Table 5. Node 2 and Node 1 are identified as the critical nodes corresponding to 300 Hz and 750 Hz resonances, respectively. In accordance with the siting strategy for ADs, an AD is supposed to be arranged at Node 2 to suppress the 300 Hz resonance, while another AD is deployed at Node 1 for the suppression of the 750 Hz resonance.

Table 5. Node participation factors of the experimental system.

Frequency/Hz	Node 1	Node 2	Node 3
300 (Mode 3)	0.3418	0.4162	0.2423
750 (Mode 2)	0.5385	0.4428	0.0199

5.3. Siting Strategy Analysis

To verify the analytical results of the siting strategy on system resonance characteristics, the inverter is adopted to inject 300 Hz and 750 Hz harmonic currents with an amplitude of 2% rated current into Node 1, and the harmonic voltage responses of each node are measured and observed. Figure 15 illustrates the time-domain voltage waveforms of all nodes as well as their FFT analysis results. It can be observed from the figure that when harmonic currents are injected at Node 1, prominent 300 Hz and 750 Hz harmonic voltages emerge at the three nodes, and these harmonic frequencies correspond to Resonance Mode 3 and Resonance Mode 2, respectively. The above results demonstrate that Node 1 and Node 2 are the critical nodes for Mode 2 and Mode 3, respectively, which verifies the accuracy of the RMA analysis.

Using Node 1, the critical node of Mode 2, as an example, ADs were installed at Node 1 and Node 3 to evaluate the influence of installation location on resonance suppression performance. Based on the experimental setup shown in Figure 13, ADs were connected in parallel at Node 1 and Node 3. The R_v of the active damper was set to 10 Ω in both

resonance frequency bands. Figure 16a,b present the voltage waveforms and corresponding FFT analysis results of all nodes under these two installation scenarios. Compared with the results in Figure 15, the harmonic voltage amplitudes at all nodes in Figure 16a,b are significantly reduced, demonstrating the effectiveness of the active damper in mitigating harmonic resonance. Since the participation factors of Node 1 and Node 3 in Mode 3 are relatively close, the suppression performance of the active damper on the 300 Hz resonance is similar in both cases. Nevertheless, the harmonic voltage amplitudes in Figure 16a remain slightly lower than those in Figure 16b. In contrast, Node 1 is identified as the critical node of Mode 2. Therefore, when the AD is installed at Node 1, the harmonic voltage amplitude at 750 Hz is substantially lower than that obtained when the AD is installed at Node 3. This result indicates that the conventional practice of installing ADs at the PCC is not necessarily the optimal solution for harmonic resonance mitigation. Consequently, the necessity of the proposed siting strategy is further validated.

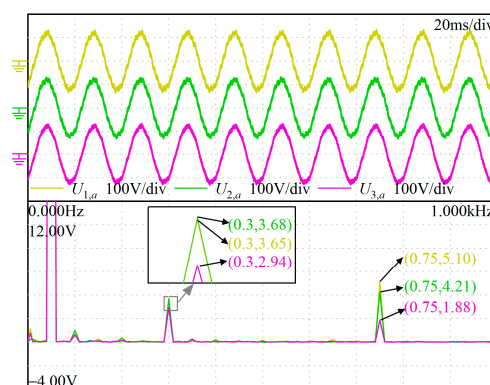


Figure 15. Experimental results of node voltages without the AD.

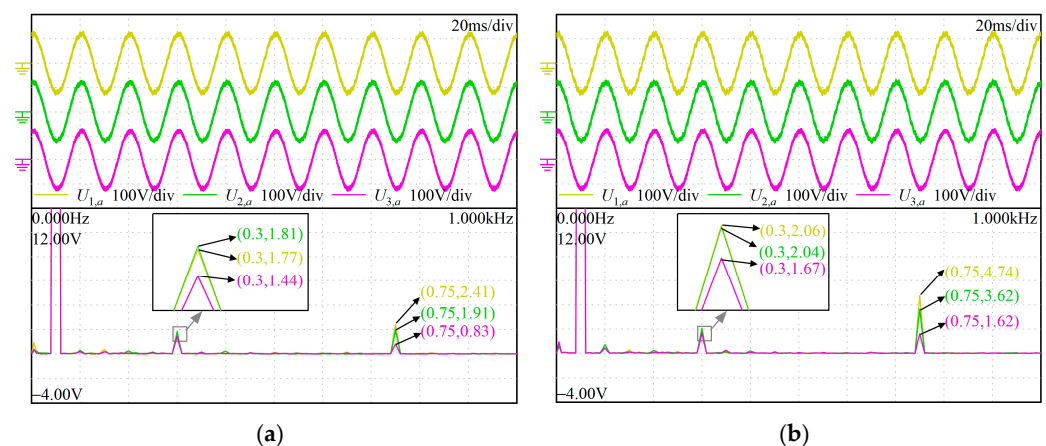


Figure 16. Experimental results of node voltages after connecting the AD: (a) Node 1. (b) Node 3.

6. Conclusions

An AD siting strategy based on RMA is proposed in this paper. This method utilizes the RMA to identify the system's resonance frequencies and calculate the PFs of various nodes. The node with the highest PF at the resonance frequency is identified as the position contributing the most to harmonic resonance in the system, representing a primary position where the system is prone to resonance. Experiments have validated that installing the ADs at these identified nodes enables effective suppression of harmonic resonance. The results also indicate that the PCC, which is typically considered the AD installation position, is not always the optimal location.

The frequency scanning method provides a feasible approach for constructing the admittance matrix of a system with unknown parameters. Furthermore, simulation results indicate that variations in grid impedance affect resonance frequencies and PFs predominantly due to the reactance component. However, for power station systems where the line layout remains stable, the selection of installation sites for AD exhibits relative stability within a specific range of grid impedance changes, without abrupt changes.

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References

1. Cai, H.; Chen, M.; Chen, Y.; Hu, C. Practical stability-oriented parameter co-design method for outer and inner loops of grid-forming converters. *J. Power Electron.* **2025**, *25*, 2321–2337.
2. Fang, T.Z.; Shen, S.H.; Jin, Y.L.; Ruan, X.B. Robustness investigation of multi-inverter paralleled grid-connected system with LCL-filter based on the grid-impedance allocation mechanism. *IEEE Trans. Power Electron.* **2021**, *36*, 14508–14524.
3. Kouchaki, A.; Nymand, M. Analytical design of passive LCL filter for three-phase two-level power factor correction rectifiers. *IEEE Trans. Power Electron.* **2018**, *33*, 3012–3022.
4. Ma, G.; Xie, C.; Li, C.; Dai, H.; Wang, Y.; Zou, J. Redesign of Current Controller to Improve Lowfrequency Stability of Grid-Following Inverters in SCR = 1 Grids. In *2025 International Conference on New Power System Technology (PowerCon)*; IEEE: New York, NY, USA, 2025; pp. 1–6.
5. Wang, C.; Pan, D.H.; Wang, X.H.; He, Y.Y.; Zhang, H.; Ruan, X.B.; Chen, X. A general graphical method for filter-based active damping: Evaluation, exploration, and design. *IEEE J. Emerg. Sel. Top. Power Electron.* **2023**, *11*, 2683–2696.
6. Li, Z.; Tang, X.; Tang, K.; Qu, B.; Wang, W.; Guerrero, J.M. An Admittance-Reshaping Control Method for Improving the Stability of Multiparallel Grid-Connected Converters. *IEEE Trans. Power Electron.* **2026**, *41*, 4680–4695.
7. Xiao, Y.; Zhang, X.; Zhan, X.; Cao, R. Design-Oriented Small-Signal Stability Assessment of Grid-Following Inverter-Based Resources Based on Virtual Dynamic Short-Circuit Ratio. *IEEE Trans. Ind. Electron.* **2025**, *72*, 8130–8141.
8. Zhang, R.; Wang, M.; Zhang, K.; Yu, R.; Zhou, L.; Yang, S. High-Frequency Broadband Resonance Compensator for the Controlled-Source Audio-Frequency Magnetotelluric Transmitting System. *IEEE Trans. Power Electron.* **2026**, *41*, 3624–3642.
9. Zhou, Y.; Liu, J.; Liu, Z. An Active Damper with Pre-Oscillation Stability Monitoring for Grid-Connected Power Electronics Systems. In *2025 Energy Conversion Congress & Expo Europe (ECCE Europe)*; IEEE: New York, NY, USA, 2025; pp. 1–6.
10. Zhuo, C.; Zhang, X.; Song, W.; Yi, H. Active Resonant Damper With Control Strategy Based on Inverter Output Conductance Optimization Under Weak Grid Conditions. *IEEE J. Emerg. Sel. Top. Power Electron.* **2024**, *12*, 2936–2946.
11. Chen, Y.; Yang, J.; Weng, L.; Yang, L. Multi-Frequency Oscillation Suppression Method for DC Bus Voltages Based on Oscillation Energy Suppressor. In *2023 IEEE 2nd International Power Electronics and Application Symposium (PEAS), Guangzhou, China*; IEEE: New York, NY, USA, 2023; pp. 1496–1501.

12. Chi, S.; Zhang, R.; Chen, A.; Cheng, C.; Sun, S.; Yu, P.; Cheng, Y. Interaction Stability Analysis and Oscillation Suppression Method of Hybrid Grid-Forming and Grid-Following Inverters System With Varying Power Levels. *IEEE Trans. Ind. Electron.* **2026**, *73*, 755–766.
13. Annuth, R.; Wichmann, A.; Becker, C. Comparative Analysis of Impedance-Based and Eigenvalue-Based Approaches for Stability Assessment. In *2025 IEEE Kiel PowerTech*; IEEE: New York, NY, USA, 2025; pp. 1–7.
14. Sun, J. Impedance-based stability criterion for grid-connected inverters. *IEEE Trans. Power Electron.* **2011**, *26*, 3075–3078.
15. Yu, C.Z.; Xu, H.Z.; Liu, C.; Chen, C.; Wang, Q.L.; Zhang, X. Stability margin analysis of multi-inverter grid-connected system considering asynchronous control period under high penetration. In *Proceedings of 2021 IEEE 12th Energy Conversion Congress & Exposition-Asia (ECCE-Asia)*; IEEE: New York, NY, USA, 2021; pp. 2080–2085.
16. Liao, S.H.; Chen, Y.D.; Wu, W.H.; Wang, L.; Xu, Q.M. Closed-loop interconnected model of multi-inverter-paralleled system and its application to impact assessment of interactions on damping characteristics. *IEEE Trans. Smart Grid* **2023**, *14*, 41–53.
17. Xue, Y.; Feng, N.; Wang, Y. Resonance Participation Factor Evaluation for Renewable Energy Systems Based on Impedance Scanning. In *2023 IEEE 7th Conference on Energy Internet and Energy System Integration (EI2)*, Hangzhou, China; IEEE: New York, NY, USA, 2023; pp. 1858–1863.
18. Li, Q.; Sun, P.J.; Lan, Y.F.; Du, X.; Luo, Q.M. Analysis of resonance characteristics of a multi-inverter grid-connected system based on resonance modal. In *Proceedings of 2022 IEEE International Power Electronics and Application Conference and Exposition (PEAC)*; IEEE: New York, NY, USA, 2022; pp. 1124–1129.
19. Cao, J.; Cheng, D.; Zhang, X.; Xia, S.; Li, G.; Sun, G.; Cai, D. Analysis of PMSG-based Wind Farm with SVG Based on Parameter Participation Factor. In *2024 6th International Conference on Power and Energy Technology (ICPET)*, Beijing, China; IEEE: New York, NY, USA, 2024; pp. 1754–1759.
20. Zhou, X.; Bu, S. Mechanism Analysis of Modal Resonance in Converter-Based Power Systems. *IEEE Trans. Power Syst.* **2025**, *40*, 3528–3542.
21. Hong, L.C.; Shu, W.T.; Wang, J.H.; Mian, R. Harmonic resonance investigation of a multi-inverter grid-connected system using resonance modal analysis. *IEEE Trans. Power Deliv.* **2019**, *34*, 63–72.
22. Hu, H.T.; He, Z.Y.; Zhang, Y.F.; Gao, S.B. Modal frequency sensitivity analysis and application using complex nodal matrix. *IEEE Trans. Power Deliv.* **2014**, *29*, 969–971.
23. Chou, S.-F.; Wang, X.; Blaabjerg, F. Frequency-Domain Modal Analysis for Power-Electronic-Based Power Systems. *IEEE Trans. Power Electron.* **2021**, *36*, 4910–4914.
24. Wang, Y.; Wang, X.; Blaabjerg, F.; Chen, Z. Frequency scanning-based stability analysis method for grid-connected inverter system. In *2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017-ECCE Asia)*, Kaohsiung, Taiwan; IEEE: New York, NY, USA, 2017.

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